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Forward-looking network analysis of ongoing sustainability transitions

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ABSTRACT

Experimentation with novel technologies mobilises resources and constructs expectations for systemic transition, yet there is limited research that examines large numbers of energy experiments. Our approach explores an idea of a patchwork of niches and contributes to transitions literature by looking beyond individual experiments. The analysis in this article identifies four clusters of sustainable energy networks (i.e. patchworks of niches), highlighting the roles of urban prosumption, rural production, small towns as integrators, and electric transport in the technological change in the Finnish energy system. The recognition of interconnections between technologies, settings and uses envisages the future scope of patchworks of regimes, and thereby provides an empirically founded, forward-looking knowledge base for political planning and development of social learning. The network analysis of the experiments was executed using Gephi visualisation and exploration software with a specific focus on energy technologies, energy sources, sites, forms of energy use and locality. A large Finnish database on sustainable energy experiments was used to identify and network connections between the core characteristics of such experiments.

1. Introduction

The perspective of socio-technical transitions has become an established way to examine long-term systemic change. The multi-level perspective (Geels, 2002; Kemp et al., 1998), in particular, has become popular among scholars as it offers a versatile view of the problematics of socio-technical transitions. This transitions framework holds that experimental innovation and an increasing structuration of activities in local practices contributes to accumulation of niches and patchworks of regimes that drive systemic change (Sengers et al., 2019; Geels, 2012, Smith and Raven, 2012). The examination of interesting or representative experiments has become a widely applied procedure for assessing technological and economic characteristics of sustainability transitions (Geels, 2002; Raven and Verbong, 2007; Verbong et al., 2008). At the same time, experimentation has become a standard praxis for developing new socio-technological solutions for sustainable energy sector transitions. We focus on both technological change and transitions in order to cover the full scope of energy sector developments, with the former accounting for incremental improvements in existing systems and the latter being more disruptive to its character.

Nevertheless, transitions in the energy system are complex in that they involve multiple and competing technologies, actors and aims. A better understanding of what is currently being experimented with helps to identify what types of technology networks are expected to progress in parallel in the near future, and to examine the technologies that are receiving less attention (Manders et al., 2018). Niches accumulate in transitions (e.g. Smith and Raven, 2012), and we argue that such accumulated niches form patchworks, which affect prevalent regimes. We rely theoretically on the concepts of sustainability transitions literature (niche, regime, nested hierarchy) and empirically on the empirical network analysis of a large number of energy experiments. Our forward-looking analysis is based on the literature on the sociology of expectations that focuses on production and circulation of expectations in science and technology (van Lente, 2012) and on the conceptualisation of experiments as a step towards accomplishing systemic innovation while accounting for social learning under conditions of uncertainty and ambiguity (Sengers et al,. 2019). Expectations and experimentation thereby create opportunities for technologies and solutions to mature (Laakso et al., 2017).

While there are a plethora of empirical transitions studies, much of

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the research focuses on either historical developments (e.g. Geels et al., 2016; Geels and Verhees, 2011; Verbong and Geels, 2007), single case studies (e.g. Penna and Geels, 2012; Quitzau et al., 2012) or single technologies (e.g. Budde et al., 2012; Markard and Truffer, 2008). Accordingly, there is limited research in transitions studies that would empirically examine a large number of experiments that share common technologies developed for varying aims (Castán Broto and Bulkeley, 2013; Köhler et al., 2019). Previous contributions with an analysis of many experimental cases have been provided, for example by Dignum et al. (2020) on urban experiments in nature-based solutions, Matschoss and Repo (2018) on governance experiments in climate action, by Antikainen et al. (2017) on the field of climate change and resource efficiency in Finland, and by van den Heiligenberg et al. (2017) on sustainability experiments in the field of geography of transitions. In addition to the scarce use of large data sets in studies, there is a research lacking in analytical data visualisation of the connections between the experiments.

Forward-looking analysis of a large number of experiments would be open in character and use the key concepts of the transitions framework to describe likely or targeted pathways that relate to sustainability transitions (Bale et al., 2015; Foxon, 2013; Loorbach, 2010; Manders et al., 2018). The examination of long-term transitions in the fields of transport and energy has benefited from the opportunity for post-reflection and has accentuated the need to connect large numbers of small developments (e.g. Geels, 2005; Geels and Verhees, 2011; Rosenbloom and Meadowcroft, 2014; Verbong and Geels, 2007). Such analyses of interconnected cases could provide a novel approach to transitions research by complementing studies of specific technologies, settings and uses, and conceptualising emerging developments as nested hierarchies and patchworks of regimes, for instance (Geels, 2002).

Contributing to the field of innovation and transitions studies, our research examines the outcomes that emerge from the detailed analysis of a large collection of energy-related sustainability experiments. Our research task in this setting is to review a large collection of energy experiments from Finland (Energiakokeilut.fi, 2016; Heiskanen et al., 2017) in order to examine how they connect in terms of technologies, settings and uses. This allows us to identify clusters of technologies and their uses that are developing in parallel (i.e. accumulation of niches and the patchworks of niches). The database was collected as a part of a Smart Energy Transitions project in 2015–2016, and its objective is to increase understanding about what various kinds of energy-related low-carbon experiments have been launched in Finland in recent years. The database presents urban and regional pilot projects with sustainable technologies, demonstration buildings, and experimentation with business models and transport systems (Heiskanen et al., 2017).

The analysis of the snapshot data over a hundred experiments, as well as their key features and settings, is used to assess the patchwork of regimes to which the accumulated and patchworked niches contribute. Our approach corresponds to the call of transitions scholars to go beyond single innovations and to include interaction between multiple systems (energy and transport, for instance) (Köhler et al., 2019; Repo and Matschoss, 2018). We further apply two core visualisations in transitions literature in our analysis: the multi-level perspective as a nested hierarchy and networks of actors (see Figs. 1 and 2 in section 2 of this article).

Next we discuss theoretically the role of experimentation in sustainability transitions in the energy system. Then we review the empirical database, which was collected in Finland in 2015-2016, to monitor experimentation in sustainable energy technologies, and present the methodology used to analyse the networks formed by the experiments. Results from our network analysis are thereafter established as directions in the energy system that rely on global technologies, local and regional solutions and national-level infrastructure. Finally, we reflect on the applicability of the results in assessing forward-looking transitions and on the idea of patchworks of niches.

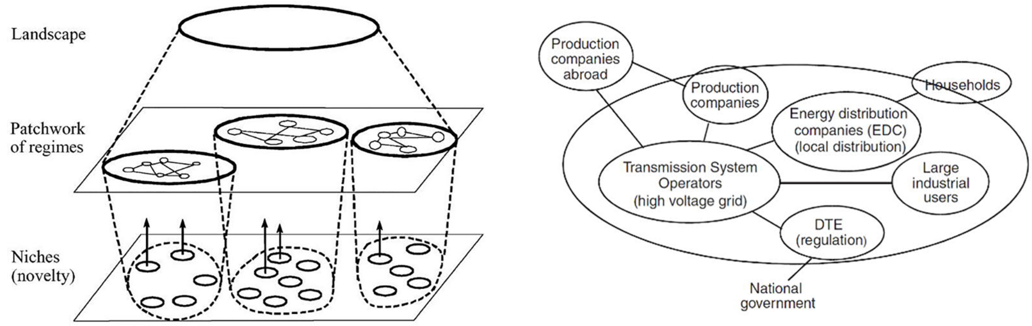
2. Theoretical setting: experimentation for transitions of energy system

Socio-technical transitions towards sustainability are frequently examined from the multi-level-perspective (MLP) framework, which considers multiple levels of socio-technical systems (Berkhout et al., 2010; Geels, 2002; Rip and Kemp, 1998). The framework argues that new micro-level challengers, such as energy experiments, are incubated in and emerge from so-called strategic niches. At the same time, pressures from the macro-level (i.e. the 'landscape') sets overarching conditions, and the meso-level (i.e. the 'regime') maintains a dynamic stability between these pressures from the niche and the landscape. In this sociotechnical setting, the regime is constituted by established activities relating to markets, policy, technology, culture, knowledge, industrial networks and infrastructure carried by different social groups (Geels, 2002). The MLP transitions framework accentuates the role of socio-technical experiments (Berkhout et al., 2009; Brown and Vergragt, 2008), suggesting that real-life societal experiments with radical new technologies take place in these niches as 'protected spaces' (Schot and Geels, 2007). The niche level is thus of particular interest in experimentation as it protects novel technologies by providing them with opportunities to mature and develop before being exposed to market competition in the incumbent regime (e.g. Geels and Schot, 2007; Smith and Raven, 2012). Technological change drives a steady creation of new niches, hence sustaining a persistent transformation of the dynamically stable system (Geels and Schot, 2007).

Strategic niche management (Kemp et al., 1998; Schot and Geels, 2008) is an approach used to guide and explain how niches contribute to the transition process. New knowledge creation and learning from experimentation in niches are considered key factors in advancing transitions (Antikainen et al., 2017; Laakso et al., 2017; van Mierlo et al., 2020; Raven et al., 2008; Sengers et al., 2019; Seyfang et al., 2014). Smith (2007) calls for more attention to the analysis of niche-regime interaction. Sustainable niches, in particular, challenge the unsustainable characteristics of the established regimes (Smith, 2007). Bai et al. (2009) also emphasise the critical role of linkages between different levels of socio-technical systems in the development of pathways towards sustainability. To capture the multiplicity of the niches and their interactions with the regime level, Geels (2002) conceptualised these dynamics as a nested hierarchy (Fig. 1). In this conceptualisation, concurring niche developments influence various regimes and subregimes, i.e. "the patchwork of regimes". Further, connections between actors in such regimes have been depicted as networks (Figure 2).

The consideration of networks is a practical way to look at the shaping of transitions, as institutionalised action creates expectations (Farla et al., 2012), and at how social learning is accrued through experimentation (Sengers et al., 2019). The sociology of expectations sees that human activities intrinsically orient towards the future. Accordingly, informal expectations circulating amongst technology developers create directions for future developments: more specifically, their decisions and activities are framed by intentions and ideas about a future situation. Expectations therefore have a performative function and can lead to the creation of a new reality (van Lente, 2012), for instance through the mobilisation of resources in sectors and innovation networks (Borup et al., 2006). Bakker et al. (2012) note that the credibility of collective expectations attributed to innovations may determine the support they receive, which in turn contributes to the accumulation of niches (see also Kern et al., 2015; Manders et al., 2018). Indeed, previous literature has found that expectations are required to start a project or an experiment (van Lente 2012) in the first place, and that expectations provide direction to science and technology developments (Rip and Kemp 1998).

Nevertheless, while expectations can be argued to mobilise and guide development, this does not imply that the connection between experiments and future solutions is straightforward. Indeed,



Figs. 1 and 2. Multiple levels as a nested hierarchy (Geels, 2002, Fig. 3, p. 1261); actors and networks in electricity regime (late 1990s) (Verbong and Geels, 2007, Figure 8, p. 1027).

expectations can turn out to be unfounded, and external factors may hinder the development of targeted solutions even if they would be considered promising otherwise. Therefore, it is valuable to consider the social learning aspects of experimentation when it relies on human agency as producers or consumers of new technologies under uncertain and ambiguous conditions (see Sengers et al., 2019). Expectations may then serve to bridge and mediate across boundaries and apparently distinct dimensions and levels (Borup et al., 2006). When expectations are accompanied by experimentation, new forms of social learnings are constructed that lead to new expectations and new experiments, and it is then useful to identify how on-going experiments interconnect. In this respect, the prevalence of networks and clusters of experiments also balances the perceived successes and failures of individual experiments. Hence, we can better discover transitions potential by examining the networks and clusters of experiments than by reviewing individual experiments.

Geels et al. (2016) reported in their comparative case study on the energy transitions of Germany and UK that these two countries have followed very different transition pathways although similar renewable energy technologies had matured in both countries. Their study concludes that variations relating to actors and institutions have contributed to substantial differences in patterns of renewable energy deployment. Farla et al. (2012) have studied the strategic roles of actors in transitions, stating that even small system changes may involve numerous actors. Frantzeskaki and Loorbach (2010) conclude that transitions in sectors particularly dependent on infrastructure (such as energy) would require experimentation by multiple actors. Transitions theories also acknowledge that the emergence of networks in niches are central to the development of protected spaces around novel technologies (Smith, 2007). Many renewable energy technologies are scalable and can be deployed in different configurations (e.g. Geels et al., 2016) and we therefore suggest that experiments with parallel technologies and networks can also determine or change the direction of transition.

Empirical studies have indeed focused on sustainability transitions and the historical pathways of developments in the energy sector. For example, Verbong and Geels (2007) have focused on developments in electricity networks in the Netherlands. Geels and Verhees (2011) have looked at Dutch cultural discourses related to the legitimacy of nuclear energy. Kern and Smith (2008) have studied the past energy system restructuring in the Netherlands, and Heiskanen et al. (2018) the incumbent energy actors facing transitions in Finland. Verbong and Geels (2010) conceptualised previous transition pathways specifically for the electricity sector and Foxon et al. (2010) studied electricity sector transition pathways in the UK. Matschoss and Heiskanen (2018) empirically examined the local enactment of transition pathways from the perspective of intermediaries as energy regime destabilisers, Marletto (2014) pathways for electric vehicles, and Canitez (2019) sustainable urban mobility in developing megacities.

Our study complements this body of empirical research by examining empirical experimentation in the Finnish energy system. While each observed experiment is typically both self-contained and embedded in its context, it has remained difficult to provide simple yet sufficiently analytical overviews of large case collections and databases. A recent example is provided by Dignum et al. (2020), who analyse a collection of 520 urban experiments. Transition dynamics, such as the accumulation of niches and the emerging patchworks of regimes that they contribute to, benefit from network analysis, which provides a technical application for reviewing large numbers of cases. Indeed, network analysis has been applied in transitions studies with a focus on biofuels and automobility (Caniëls and Romijn, 2008; Manders et al., 2018).

3. Renewing the energy regime in Finland: data and methodology

The challenge and opportunity of energy transitions have been addressed in Finland in two contrasting ways: by striving to be the Western leader in new nuclear energy production and by boosting opportunities for the production and consumption of sustainable energy, albeit on a much smaller scale. The former represents a continuation of operations in the current Finnish energy system while the latter represents systemic transitions towards new energy sources, technologies and solutions, and incorporates experimentation as a mechanism for advancing transitions.

The Finnish energy regime exhibits high energy consumption per capita due to energy-intensive industry, especially in forestry, which exports much of its production. Industry consumed almost half of all energy used in the country (47%), heating of buildings 25%, traffic 16%, and other uses accounted for 12% in 2018. The portfolio of energy sources in Finland is diverse. Wood-based energy sources formed a share of 27%, oil 22%, nuclear 17%, coal 8%, gas 6% and import of electricity, peat, water and wind, and others each 5% of the total energy consumption in 2018 (Statistics Finland, 2019). During the first decades of the new millennium, the energy sector has shown rapid advancements in the development of smart energy grids: by the end of 2017, 99% of consumption locations had smart metering (Energy Authority, 2018) with Finland being one of the leading countries in the world. On the other hand, the developments in the renewable energy sector such as wind or solar power have not been as fast as those in many other European countries. For example, the cumulative capacity of wind power by 2016 was only 1533 MW and, by 2019, 2284 MW in Finland (Finnish Wind Power Association, 2020), whereas in Sweden the capacity was 8985 MW and in Denmark 6128 MW in 2019 (Wind EUROPE, 2020). In 2017, the share of wind electricity of the total generation of electricity was 50% in Denmark, 11% in Sweden and 8% in Finland (Nordic Energy Research, 2020).

A special characteristic of the energy regime in Finland is a high reliance on combined heat and power (CHP) in energy production: circa one-third of heating of households originates from CHP (Statistics Finland, 2019), which creates a further challenge for the energy sector transition due to the government policy to phase out coal in energy production by 2029. In the future, the Finnish energy regime will rely more on the production and consumption of electricity when coal is phased out, the on-going growth in renewable energy capacity continues, and two new nuclear energy production plants are constructed. The Finnish economy continues to rely on the forest industry, and at the time of the collection of the database, the government in office had a strategic focus on the creation of a strong bioenergy sector and especially biofuels (Finnish Government, 2015). The targets of the long term National Energy and Climate Strategy for 2030 include the reduction of greenhouse gas emissions by 2030, increasing renewable energy use and self-sufficiency in energy supply, increasing renewable energy use in transport, halving the use of imported oil for energy and phasing out coal in energy production. The respective national strategy report for 2017 highlights the role of biofuels and electric transport and promotes electricity and heat production from renewable energy sources (Huttunen, 2017).

Following the long-term strategy, the focus on electric transport intensified at the beginning of 2010, when there were hardly any electric vehicles in Finland. When the database was collected, the numbers of electric vehicles were very limited (844 battery electric and 2441 plug-in electric vehicles in 2016), but they have grown rapidly since then (2661 and 24 704 respectively in 2019) (Finnish Transport and Communications Agency, 2020).

Experimentation has become a common way to target such transitions (Berkhout et al., 2010; Brown and Vergragt, 2008), which is a complex task that interconnects people, technologies, and infrastructures and their use. In the upcoming sections, we present our research data and describe the data visualisation methodology that we use to review such interconnections. The data has been extracted from an open database on energy experiments in Finland (Energiakokeilut.fi, 2016).

3.1. Database on energy experiments in Finland

Taking practical cues from how network analysis has been carried out in transitions studies (Bakker et al., 2015; Caniëls and Romijn, 2008; Manders et al., 2018; Wen et al., 2015), we examine connections between energy experiments to assess which networks are expected to progress together in the near future, and to which fewer experimental resources have been dedicated. We use data from the Energiakokeilut ('energy experiments') database, which contains over 100 carefully and systematically collected Finnish cases on recent and ongoing experiments that develop new technologies, configurations of technologies, novel solutions or services, and have taken place in real-life settings focusing on the development of a more sustainable energy system. Our specific focus is on the connections between energy technologies, sources, sites, forms of energy use and localities as exhibited in the experiments. Such an approach attempts to circumvent both the limitations of examining a limited number of cases and the sometimes overly universal character of statistical analysis. Indeed, standard approaches to examine such databases include case studies (see Yin, 2009) and statistical analyses to test hypotheses (Castán Broto and Bulkeley, 2013; Dignum et al., 2020; Matschoss and Repo, 2018).

The database of energy experiments examined included, at the time of the study, 113 energy-related pilot projects, demonstrations, field trials and local experiments. Its data was collected in 2015–2016 in the 'Smart energy transition' research project, in order to gain a better understanding of the technologies experimented with in Finland. The project examines the disruption and transitions of the Finnish energy sector towards sustainability, and the database is publicly accessible at www.energiakokeilut.fi. The experiments were selected for inclusion if they experimented with technology that is new in the Finnish context, current technology on a new scale, or new ways of organising energy services (Energiakokeilut.fi, 2016). The organisers of the experiments were contacted personally via email to verify the accuracy of the data of their experiment, which was collected by the researchers using publicly open material (Heiskanen et al., 2017). The organisers were also given the opportunity to send additional information on their experiments after the inspection of their case.

Database descriptions provide information on the types of experimentation conducted in Finland, and show the wide variety of experimentation in terms of how and where novel solutions may disrupt the established system. The database thus does not aim to present all energy experiments conducted in Finland but attempts to cover as many types of experimentation with a transition focus as could be identified. The project was initiated during a time when the Finnish government established a 'culture of experimentation' as one of its strategic means to renew Finnish society, attempting to learn from grassroot activities and heavily transform governance structures (Finnish government, 2015).

The focus of the database is on energy technologies, energy sources, sites, forms of energy use and locality. Each category further includes more specific key characteristics as database codes. For instance, 'energy technologies' includes batteries, solar heat, heat pumps, and wind power while the category of 'energy sources' considers solar, biomass, wind, and waste (Energiakokeilut.fi, 2016). All experiments included in the database are coded according to these keywords, which is why this empirical database is suitable for the network analysis performed in this study. Box 1 presents in short how an experiment on Farm Power (Kallio et al., 2020) is described in the database.

The database is designed to be used by public authorities, politicians and media as it offers them insights into where Finland stands in terms of developing and adopting novel procedures related to renewable energy and other low-carbon solutions. It is also intended to be used by researchers and organisers of demonstrations, pilots or local experiments in order to provide examples of experiments that have been initiated in Finland and to increase knowledge sharing and upscaling (Energiakokeilut.fi, 2016). The experiments in the database include urban and regional pilot projects utilising sustainable technologies and practices, demonstration buildings or installations, experimentation with new business models or new organisational models for the purchasing, management or use of sustainable technologies, and experimentation with new transport systems (Heiskanen et al., 2017).

3.2. Network analysis of experiments in the Finnish energy transition

We use the encoded characteristics ('codes') of the experiments to examine and illustrate networks. The codes were translated from Finnish into English and paired according to each experiment, after which the code pairs were connected and visualised in the form of networks with the Gephi visualisation and exploration software (Bastian et al., 2009). Table 1 below lists the statistics of the data used in the analysis. The data includes 4601 pairs of codes, and there are 1258 unique pairs. The analysis uses the frequency of code pairs to

Box 1
An example from the database: Farm Power.

Farm Power is a service that creates a marketplace for consumers to buy electricity produced by other consumers, so-called prosumers, which is operated by an incumbent energy company, Oulun Energia. With the Farm Power service, the producers can offer their excess electricity to the market and set the price for the electricity. The electricity delivered is produced in Finnish micro- and small-scale power stations that use solar-, wind- and hydropower plants, as well as bio- and wood gasification generators. Farm Power is thus a novel business model that enables small-scale producers to offer electricity to consumers in the market at a price that they have set.
Type of experiment: *company pilots*
Energy sources coded for the experiment: *solar, biomass, wind, water*
Energy technologies: *photovoltaics, biogas plant, CHP plant, wind power plant, hydropower plant*
Form of energy use: *electricity*
Locality: *rural, farm*

Table 1
Description of data analysed.

Number of experiments and pairs of codes	Most popular pairs of codes
113 experiments	solar, electricity: 46
4601 pairs of codes	heat, electricity: 43
1258 unique pairs of codes	solar, photo voltaic: 39
	solar, heat: 39

illustrate the network. The most frequent code pair concerned 'solar' and 'electricity', followed by 'heat' and 'electricity', already giving us an idea of the energy sources and usage that receive the most attention in experimentation.

The Gephi visualisation enables the examination of the networked character of a developing industry as it brings together actors, technologies and energy sources as well as localities. Clustering further helps us identify how these are related. Accordingly, network analysis accomplished with Gephi has been used to examine ICT-related automobility experiments (Manders et al., 2018), niche accumulation and standardisation (Bakker et al., 2015), and transitions in water management (Wen et al., 2015). These studies have in common the aim of examining how emerging technologies are connected to actors and how transition pathways are being constructed in networks, which may cross established professional boundaries.

The unique pairs of codes and their frequencies are used to form networks in Gephi. Fig. 3 depicts networks, which consist of the codes (as nodes) and connections between them (as edges). The size of a node represents its connectivity to other nodes and the lines between the nodes indicate connections. The layout of the graph was created with the ForceAtlas2 algorithm, which is an all-round solution for depicting networks on a map and suits the qualitative analysis of small and medium-sized graphs (Jacomy et al., 2014). The modularity algorithm is applied to the data to identify clusters, which differ from random distribution (Blondel et al., 2008). The unsupervised algorithm works in two phases as it first identifies small clusters of nodes and then aggregates nodes in these clusters to build a new network until maximum modularity in the data is achieved. This procedure clusters codes and reveals hard-to-see interdependencies, and allows us to see linkages of subsystems of energy regimes that co-evolve together, such as energy production and mobility.

4. Results: patchworks of niches

Network analysis is a method for showing interconnections between observed objects. In this study, we analyse how the key characteristics of the examined experiments on sustainable energy connect. The characteristics and their connections are further visualised as clusters, which are presented in Fig. 3. The figure covers the connections between the characteristics (i.e. codes) of the 113 examined experiments. The various colours illustrate the four network clusters formed by the characteristics of the energy experiments and identified by the applied modularity algorithm (Blondel et al., 2008). Nodes and edges, in turn, are depicted as circles and lines, which represent their degrees of connectivity: larger circles indicate greater connectivity to other nodes, while lines indicate connections between pairs of nodes.

The figure shows that four clusters emerge in the data on energy experiments. These clusters form patchworks of niches and are recognisable entities while they also connect to each other (see Blondel et al., 2008). For instance, the connections between waste, combined heat and power production, biogas plants, and storage can be observed in the purple graph cluster, while they connect to other clusters to a lesser extent.

We have labelled these clusters 'Urban prosumption' (green cluster), 'Rural production' (purple cluster), 'Electric transport' (blue cluster), and 'Small towns as integrators' (the orange cluster). This labelling represents a first characterisation of the network clusters and indicates that there is a connection between geographical scales and experimental characteristics. We next present the rationale for the labelling as well as a more detailed examination of the cross-industrial clusters.

Cities are key locations in the experimentation cluster 'Urban prosumption' (in green). Experimental solutions take place at the residential level, and experiments relate to buildings, for instance through energy prosumption (i.e. productive consumption), use of LED lighting, ground and air heat pump technologies as well as solar heat and power technologies. These experiments in urban energy prosumption connect

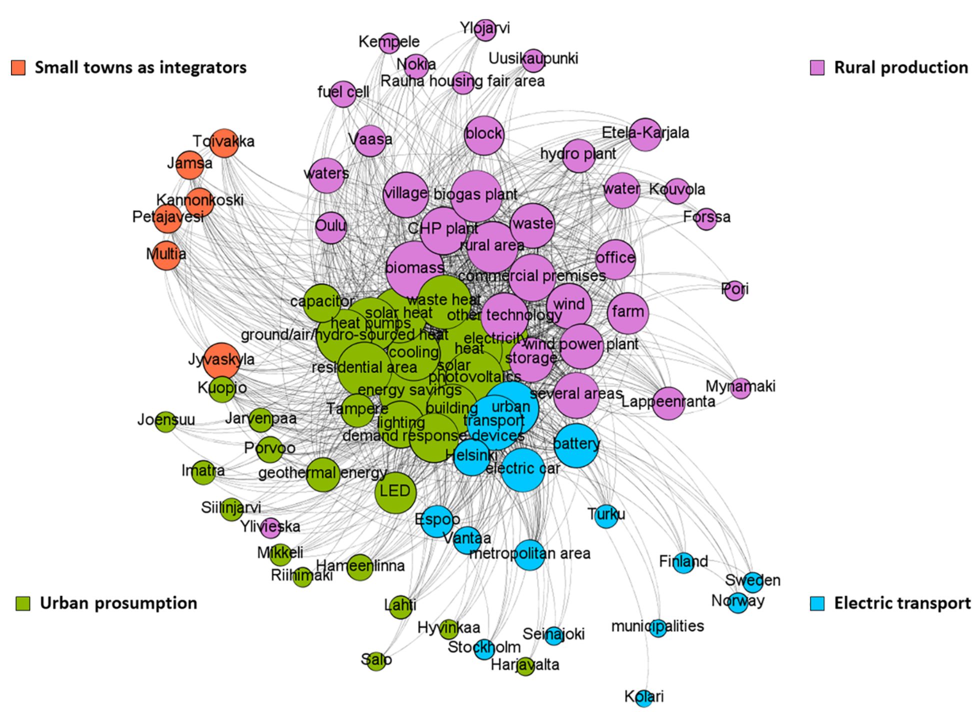


Fig. 3. Patchworks of niches of energy pilots and experiments.

global technologies and local renewable energy sources. The technologies experimented with are easily transferable and applicable in many contexts, especially urban ones. These technological solutions frequently include a strong focus on solar energy as an energy source and contribute to several experiments in the database. These technologies can be experimented with by individual innovators as lay consumers or local residents relating to solutions installed in buildings. Practical examples of such experiments include joint purchases of solar panels for households, pilots relating to the installation of solar panels in commercial buildings, and virtual power plants offering demand response.

The experimental cluster on 'Rural production' (in purple) connects waste, combined heat and power production, biogas and hydro plants, and storage. This takes place mostly in smaller municipalities and focuses on the production rather than the consumption of energy. The network analysis shows that municipalities participate in experiments that target regional or local solutions, technologies and energy sources. In effect, these experiments connect rural energy production with local energy sources: biogas, biomass and CHP plants, farm energy production as well as commercial premises and offices. Further, experimentation that is connected to power plants or other established infrastructure often requires the involvement of local authorities, such as municipalities. Examples of rural experiments include efforts to develop energy ecosystems and energy communities, smart grid pilots and establishment of wind power plants for self-sufficiency.

'Electric transport' (in blue) emerges as a third major experimental cluster. It connects urban transport, electric cars and battery technologies, as well as the nation-states Finland, Sweden and Norway. Additionally, large cities in the Helsinki metropolitan area in particular connect to experimentation with electric traffic solutions. Examples of such experiments include development and first-stage deployment of a national-level charging network and trials with electric buses in large cities.

Finally, the cluster 'Small towns as integrators' (in orange) connects to both the clusters of 'Urban prosumption' and 'Rural production', but does not have an independent experimental focus per se. This cluster identifies small towns and municipalities that are active participants in energy experimentation and have adopted hybrid strategies that cover both urban and rural opportunities in energy transition. Such integrative experiments include the establishment of a training and research centre for renewable energy, and an industrial incubator for SMEs in the field.

While clusters of technologies and their uses can be identified, the applied network approach also acknowledges interconnections between the technologies and uses evident in the clusters. For instance, the pioneering Hinku network, which consists of municipalities striving for carbon neutrality, mobilises activities concerning solar panels and replacement of fossil energy sources in heating. Similarly, the smart city pilot in the suburban Joenkylä-Utra area of the city of Jyväskylä connects energy and resource measures with information technologies when apartment blocks are modernised. Both are examples of how urban prosumption connects to rural production in the field of sustainable energy, and provide cross-industrial opportunities for social learning.

The identified patchworks of niches (i.e. clusters) are presented in Fig. 4 in the conceptual model depicting multiple levels as a nested hierarchy (Geels, 2002). This procedure not only respects the forward-looking perspective of the experiments examined, but also positions them in a key conceptualisation of systemic change. As for the data from the experiments, only major connections between nodes are presented, representing a degree range between 35 and 73, which means that the least frequent connections are omitted from the visualisation. For example, the small towns present at the outskirts of Fig. 3 have then been filtered out and the experimental differences between the clusters highlighted. Indeed, the clusters contribute to a potential future patchwork of energy regimes.

When we apply the results in the conceptualisation of the transitions framework, it is possible to highlight the potential of experiments and collections of their key characteristics to rise from the niche level to a patchwork of energy regimes. This idea is supported by the fact that the energy industry is in transition and established market players are participating in the transition. Considering investments in energy production capacity in Finland in 2016, a clear trend is visible: capacity has been reduced in traditional condensing power (2250 MW since 2010) and new capacity has been built, especially in wind power production (1743 MW) (Pöyry, 2016). Hence, shifts from niches to regimes are expected to take place even if some players attempt to hinder or slow down such transitions for reasons of business strategy.

While many energy technologies can be considered truly global, much of their application requires local adaptations. The results suggest that new energy solutions, which are applied in urban prosumption settings, are of global character. While the selection of such global technologies is to be suited to Finnish urban contexts, they nevertheless require less domestication than technologies in the other potential regimes. Similarly, the regime of electric cars relies on global technologies, which are applied at the level of national systems. This is because Finland does not produce electric vehicles on a large scale, but needs to construct infrastructures such as a network of charging stations and standards for the charging of vehicles for electric transport to function at the national level.

Rural production, on the contrary, requires local and regional adaptations of technologies. The development of power plants, for instance, needs to consider available energy sources and distribution networks. The local and regional levels are able to utilise a large variety of production scales, ranging from small-scale energy production for full or partial self-sufficiency on farms to fully-fledged power plants serving hundreds of thousands of consumers.

A review of how the results appear in nested hierarchies verifies that the conceptualisation performs well at the level of detailed and miniscule data. At the same time, the procedure highlights a feature that is evident but could be better accentuated in the conceptualisation. The application of networked data stresses that there are connections between readily identifiable clusters of technologies. The results are further compatible with the conceptualisation of the nested hierarchy, and suggest that the accumulation of niches can be depicted as networks in addition to patchworks as in Fig. 1 (Geels, 2002). At the risk of introducing ambiguity into the conceptualisation, it could be worthwhile to portray the patchworks of niches and regimes as overlapping and porous, as we have attempted to do in Fig. 4, which may be due to the character of energy and its importance in all sectors of society.

An analysis of concurrent and networked energy experiments also draws attention to integrative and missing connections. For instance, storage technology links to all clusters, and thereby forms an integrative technology. In the cluster 'Rural production', storage is required in energy production, whereas in the other clusters it forms a prerequisite for the use of energy. This result reflects the current market situation in Finland well, as there is only a limited selection of commercially available storage solutions and the business field is just emerging.

Conversely, the connection between electric cars and solar energy appears missing. Electric cars can act as demand-responsive storages of excess electricity produced by solar panels, and battery storages and photovoltaic solutions are both developing rapidly. Yet, these solutions are not sufficiently mature to be empirically experimented with in Finland, and it can thus be expected that such vehicle-to-grid innovations are likely to be developed in other countries than Finland.

5. Discussion and conclusions

Experimentation has become a commonplace strategy in the development of sustainable energy production and consumption. The literature argues that experimentation provides better systemic opportunities in transitions towards sustainability (Schot and Geels, 2007;

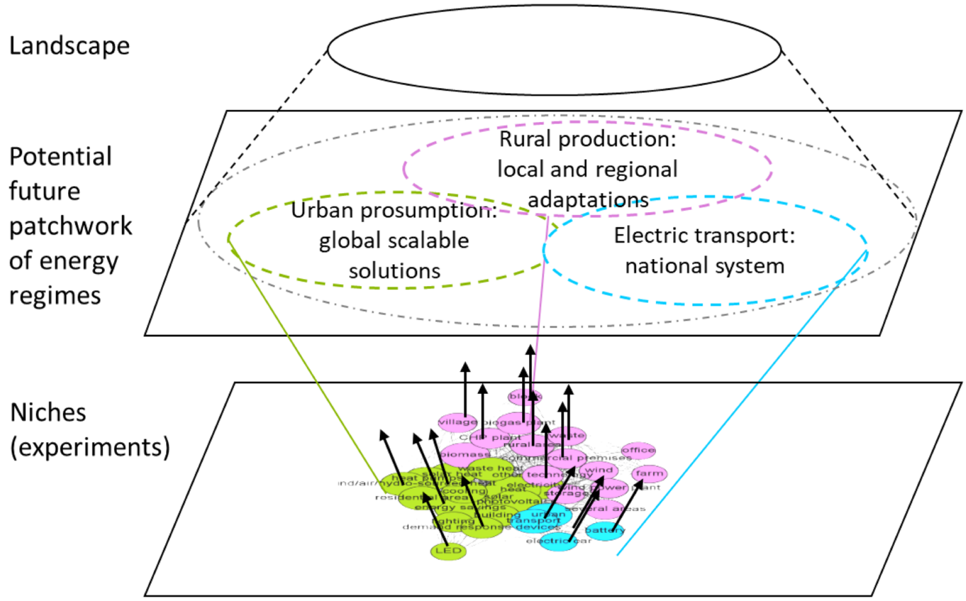


Fig. 4. Potential Finnish future patchwork of energy regimes emerging from the key patchworks of niches.

2008). Experimentation is built on and builds expectations and hence mobilises transitions (Bakker et al., 2015; Borup et al., 2006). At the same time, experimentation offers opportunities for social learning that also transcend specific undertakings (Sengers et al., 2019). The latter is something that network analysis is well equipped to contribute to because it can be used to identify technologies and solutions that progress in parallel in observed clusters. This is an interesting issue particularly in the field of energy, which can be produced and consumed in various forms.

We have applied network analysis as the methodology and data visualisation in the presentation of our results. The network approach to examining transitions is particularly suitable for connecting parallel developments that influence regimes, as well as connecting cross-sectoral developments. We have examined energy experiments beyond the perspective of individual case studies and thereby provided novel, systemic knowledge on sustainable energy transition. In doing so, we opted to account for key characteristics of energy experiments conducted in Finland.

The key contributions of this article for transitions research in the energy field is the identification of interconnections between features of energy experiments, and the establishment of how these features constitute clusters of evolving technologies as patchworks of niches. 'Urban prosumption', 'Rural production', 'Electric transport', and 'Small towns as integrators' are the four clusters evident in the analysis, and while there are connections between the clusters, they nevertheless form independent entities in sustainable energy. The clusters depict distinct sets of technologies, uses and settings, and merit further attention when attempting to examine how the sustainable energy field is progressing and how it should be directed. For instance, while electric vehicles belong to the cluster 'Electric transport', they arguably connect to the other clusters due to converging technologies in energy production, storage and distribution. When facilitating sustainable energy transitions, this is an opportunity that should be looked into as the electrification of energy progresses further.

Examining the results from the perspective of sought transitions offers interesting insights. The results that are presented as networks draw attention away from niche management of single technologies by examining technological development beyond specific experiments. The development of combined heat and power production (CHP), for instance, is of key importance when advancing sustainability transitions. It is currently considered an energy-efficient mode of production, but the phasing down of coal will require new solutions, which go beyond improving its current form. In our network analysis, it is accordingly positioned among experiments in rural production, which is concerned with biofuels and waste.

While biogas is prominent in the experiments, at a more systemic level, biofuel does not emerge as a way to advance the "greening" of transportation, which is another key challenge in transitions. Interestingly, electric transport emerges as a self-reliant cluster instead, and it targets national-level systems and large cities, while not connecting to rural production of energy forms such as biogas. The "greening" of consumption, in turn, takes place in cities through energy efficient prosumption, in which excess energy is reused and solar energy produced. Such renewable energy sources differ from rural production in that they mostly take place at the micro level in buildings, and near the source of energy production. Renewable energy sources in rural settings, in contrast, serve more extensive use outside the production areas. As the experimental renewable energy solutions advance in the distinct clusters and are applied differently across settings, they will draw from contrasting resources for further development and rely on varying expectations and produce different kinds of social learning.

The network analysis applied has its limitations, which mostly relate to the data used. While many experiments were examined, the results nevertheless depict information from that particular database. For this reason, it is not possible to examine missing experiments, missing connections between them or opportunities for novel ones, for instance, without considering additional data. In the upcoming section, we attempt this by reviewing the results obtained against policy objectives. Similarly, the examination of coded characteristics of experiments allows for connecting these characteristics but further analysis would be required to connect the experiments themselves. This has not been in our focus as our objective has been to identify clusters of energy technologies and uses in order to review, at a more conceptual level, how sustainable energy is being experimented with.

The network approach and the results it produces may contribute to the better formulation of public policy for sustainability transition as well as the alignment of sectoral energy policies because they reveal interconnections and thereby can reduce insecurity regarding where the energy field is heading (see Geels et al., 2018; Matschoss et al., 2019). Previous research has also found that policy instruments that stimulate network building and learning can be highly important in forming transition pathways (Verbong and Geels, 2010). Our research can thus support policies that, for example, require knowledge of the existing and potential energy networks, aim to increase cross-sectoral networking in desired directions, or encourage experimentation with new technologies.

The data visualisation of experiments also offers an empirical basis for the evaluation of policy measures. For example, the National Energy and Climate Strategy for 2030 directs activities towards the long-term climate targets in Finland (Huttunen, 2017). Electric transport and biofuels are highlighted in the strategy. Our analysis shows that experimentation, and therefore also social learning, is substantial concerning the former but limited concerning the latter. Analysis results such as these can support the reformulation, implementation and monitoring of the impact potential of public policy. Another empirical example of the usefulness of such networks for informing public policy is the development of combined heat and power production (CHP), which becomes necessary when coal is phased out and needs to be replaced with other energy sources. Its key role for the energy transition is recognised in the policy document and policy measures at the time of the collection of the database, and is addressed especially in rural and small town contexts. While this is a reasonable context today, it is likely that novel solutions for CHP may emerge from urban prosumption in terms of solar and ground-source heat, and network analysis of ongoing experiments may be used to identify suitable opportunities for interconnections.

In our work, we have also demonstrated that the core conceptualisations developed in transitions research work well with the analysis and visualisation of detailed data (see Geels, 2002; Verbong and Geels, 2007). For transitions studies, our work confirms that the core conceptualisations can be applied in the identification of progressing sociotechnical networks. The analysis of the snapshot data from over one hundred experiments and their key features and settings was used to assess the potential patchwork of future regimes, which the experiments contribute to. We also demonstrate that the network approach can also be used to examine large data sets in greater detail. Earlier research has highlighted the critical role of linkages between different levels of socio-technical systems in transition, and analysed those with the Gephi data visualisation tool as real-life experimentation networks. Through the examination of networks and clusters of experiments, it is possible to identify transitions potential, which may remain hidden if only individual experiments are reviewed. Future studies can benefit from the demonstrated data analysis and visualisation methodology, which allows detailed analyses of the accumulation of niches, patchworks of niches, patchworks of regimes and their interrelations. A further interesting opportunity would be to examine how configurations at niche and regime levels evolve over time.

Author statement

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